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The hydrology and hydrochemistry of six small playas in the Yarra Yarra drainage system of Western Australia

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Abstract

The hydroperiod, filling frequency, local shallow groundwater movement and surface water and shallow groundwater chemistry of six small (< 3km^2) playas from the Yarra Yarra drainage system of Western Australia were monitored from September 2002 to June 2004. The playas are morphometrically similar and adjacent and represent a hydrological continuum of ephemeral basins ranging from mostly wet (Mongers B) to mostly dry (Kadji A). Hydroperiod ranged from 19 to > 211 days and filling frequency from 1 to 3 cycles over the study period, reflecting rainfall and sub-catchment variability. The playas are net discharge points for groundwater. However, small local vertical head variations suggest that groundwater does not discharge at the same rate across the playa surfaces and that playas may have short-lived recharge phases. Chemically, the playas are typical of salt lakes in Australia. Surface waters showed an ionic dominance consistent with seawater with minor variations attributed to transitional phases in the geochemical evolution of the waters. Shallow ground waters showed a common and consistent pattern of ionic dominance: $Na^+ > Mg^{2+} > K^+ > Ca^{2+}$: $Cl^- > SO_4^{2-} > HCO^{3-} > CO_3^{2-}$. A geochemical pathway of brine evolution is proposed.

Keywords: hydroperiod, Yarra Yarra, playa, hydrochemistry, ground water

Introduction

The hydrology and hydrochemistry of six small playas in the Yarra Yarra drainage system of Western Australia were investigated between September 2002 and June 2004. Serious catchment degradation, including modifications to catchment hydrology and hydrochemistry through secondary salinisation and related processes threatens the ecology of the lakes (Williams 1999; Clarke 2001; Clarke *et al.* 2002; Boggs *et al.* in press). It is clear that the naturally occurring playas of the Yarra Yarra drainage system are ecologically important wetlands which perform crucial structural and functional roles for the wider Yarra Yarra catchment. These include supporting a diverse suite of aquatic organisms as well as providing habitat to rare migratory birds. Several unique and rare organisms are known to inhabit the lakes including a new species of giant ostracod (Crustacea) *Australocypris mongerensis* (Halse & McRae 2004) and the rare wading bird, the hooded plover (*Thinornis rubricollis tregellasi* Mathews, 1912) (Marcus Signor, pers comm.) which is listed on the 2006 IUCN Red List Category as a near threatened species (BirdLife International 2006). Additionally, the playas may have significance for human well-being and economy. It is therefore important to understand their structure and function.

Playa hydrology, particularly variations in hydroperiod, whether linked to climate and catchment variation and/or anthropogenic modifications has implications for playa ecology through water chemistry characteristics such as salinity and ionic composition (Williams *et al.* 1990; Saros & Fritz 2000a; Radke *et al.* 2003), including the prevalence of waterbirds (Halse *et al.* 1994; Chapman & Lane 1997; Roshier *et al.* 2001, 2002), the distribution of macrophytes (Brock & Lane 1983) and invertebrate populations (Williams 1998). It also influences lake morphology through surface water shaping processes (Bowler 1986; Timms 1992; Boggs *et al.* 2006). Groundwater movement and groundwater – surface water interactions are also an important control of both playa morphology (Bowler 1986) and the chemical evolution of lake brines (Bowler 1986; Torgersen *et al.* 1986; Jankowski & Jacobson 1989).

Thus, given the importance of playa hydrology and hydrochemistry to many aspects of the playa environment, the main objectives of this research were to: relate patterns of hydroperiod and filling frequency and to rainfall and catchment characteristics; characterise local, shallow groundwater movement; and measure variability in surface water and shallow groundwater chemistry.

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Setting

The Yarra Yarra drainage system is located in the Yarra Yarra catchment approximately 300 km north-east of Perth, Western Australia (Fig. 1). Stretching for over 300 km, the drainage line is comprised of a chain of over 4, 500 interconnected playa lakes (Boggs *et al.* 2006). In the lower Yarra Yarra drainage system, small playas, *i.e.* those with an area < 10 ha, constitute 51% of the total number of playas reaching spatial densities of > 15 playas/km^2 (Boggs *et al.* 2006). They are highly responsive to rainfall and runoff events and show great variability in hydroperiod across the catchment. Thus the research presented here focuses on this type of wetland.

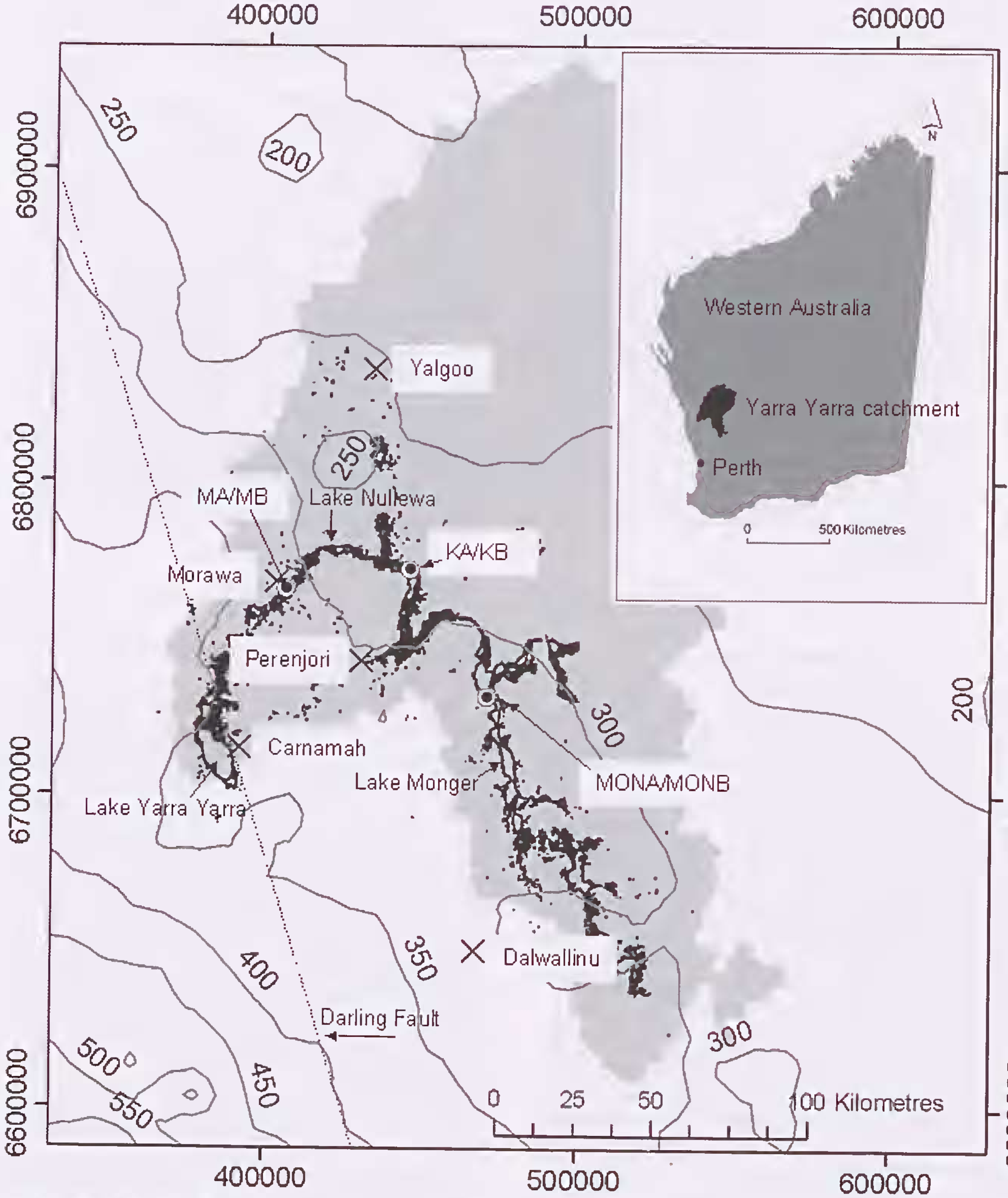

Figure 1. The location of the Yarra Yarra catchment in Western Australia showing the location of the study playas in the Yarra Yarra drainage system; annual rainfall isohyets (data derived from Taylor, 2001) and climate averages at three locations in the Yarra Yarra catchment; (a) Yalgoo; (b) Morawa; and, (c) Carnamah (data from Bureau of Meteorology, 2004).

Geomorphology and geology

The evolution of the modern Yarra Yarra drainage system began in the Pliocene (Yesertener 1999). Due to a combination of tectonic uplift and increasing climatic aridity, the palaeodrainage became landlocked and has became progressively saline (Beard 1999, 2000) through the concentration of aerosol salt from the sea (Chivas *et al.* 1991). Detailed accounts of the geomorphology of the Yarra Yarra system are given in Killigrew & Gilkes (1974), Beard (1999; 2000) and Boggs *et al.* (2006).

Surficial alluvial and lacustrine sand and clay of ~5 m thickness overlay Tertiary palaeochannel deposits in the Yarra Yarra salt lake valley (Commander & McGowan 1991). The catchment is divided into two major geologic subdivisions by the Darling Fault: sedimentary lithology to the west and Achaean granite and granitic gneiss to the east (Flint *et al.* 2000).

Climate

The Yarra Yarra region is characterised by hot, dry summers and warm, wet winters (Gentilli 1971, 1993) (Fig. 1). Annual average temperatures range from 12.5 – 27 °C and the annual average evaporation rate is approximately 2000 mm (Bureau of Meteorology 2004). Reliable rainfall occurs between May and September, although localised thunderstorms and cyclones can bring heavy summer and autumn precipitation (Henschke 1989; Yesertener *et al.* 2000). For example, above average annual rainfall occurred in the region in 1999 with 46% of the total rainfall recorded at Carnamah falling during the autumn months (Bureau of Meteorology 2004). Annual average rainfall ranges from 200 – 400 mm across the catchment, becoming progressively drier from southwest to northeast (Fig. 1). This rainfall gradient creates variability in lake hydroperiod across the catchment area. This has not been systematically evaluated, however observations of the authors and others (Brock & Lane 1983; Henschke 1989) indicate that hydroperiod is generally short, usually only a few weeks in duration.

Groundwater

Groundwater underlies the entire catchment at variable depths and the watertable tends to follow the topography (Henschke 1989; Clarke 2001). Depth to groundwater is generally less than 10 m (Commander & McGowan 1991) in the dominant granite and gneiss geology (Flint *et al.* 2000) and fluctuates in response to seasonal rainfall (Speed & Lefroy 1998; Speed 2001a, b). These groundwaters progressively increase in salinity, to > 200 g/L and rise to within 2 m of the surface with increasing proximity to the salt lakes (Commander & McGowan 1991).

Groundwater flow is from the flanks of the valley towards the chain with an inferred component of flow downstream, *i.e.* from Lake Mongers to Yarra Yarra with each playa acting as a discharge site. Yesertener (1999) investigated the groundwater discharge from Lake Yarra Yarra and concluded that the groundwaters are linked to the Moore catchment and active Moore River to the south through the underlying Tertiary palaeochannel aquifer.

Hydrochemistry

The hydrochemistry of playas in Western Australia has not received the same scientific attention as salt lakes of south-eastern Australia (see Radke *et al.* 2002, 2003). Surface waters of the Yarra Yarra lakes have been sampled sporadically over the last 20 years (Geddes *et al.* 1981; Brock & Lane 1983; Cruse *et al.* 1989; Regeneration Technology 2001; Smith 2001). They are similar in water chemistry to other Australian inland salt lake systems in that they have alkaline, NaCl dominated brines. Salinity varies greatly between lakes and fluctuates widely in the same lake over time. The pattern of ionic dominance is typical of sea water like the majority of salt lakes in Australia (Drever 1982; Herczeg & Lyons 1991). Ground waters are dominated by NaCl and pH ranges from 3 – 9.8 but is predominantly alkaline near salt lakes.

Methods

As there are in excess of 4, 500 playas in the Yarra Yarra drainage system, a representative six small (< 3 km^2) playas, three pairs of adjacent playas from different sub-catchments, were chosen for study and identified as Mongers A (MONA), Mongers B (MONB), Kadji A (KA), Kadji B (KB) Morawa A (MA) and Morawa B (MB) (Figures 1 and 2). The playas were chosen for their morphological similarity, summarised in Table 1, but each pair were chosen from a different hydrological environment to allow the investigation of hydrology and hydrochemistry across a hydrological continuum.

Catchment analysis

The local sub-catchment of each pair of playas was derived to examine the relationship between catchment characteristics such as size, slope and drainage connectivity to playa hydrology. Five metre contour data made available by the Yarra Yarra Catchment Management Group (Taylor 2001) were used in the ESRI Arc GIS 9.0 software package to generate digital elevation models (DEM) and define connected drainage networks and catchment boundaries for MONA/MONB and MA/MB. The equivalent contour data were not available for the KA/KB catchments, therefore elevation data were derived from the 3 second DEM (Geoscience Australia 2005). Data are regularly gridded at 3 seconds of latitude and longitude (approximately 100 m) from the Shuttle Radar (SRTM).

Surface water measurements

Surface waters were sampled from the middle of each playa and maximum lake depth recorded approximately weekly during wet phases from gauge boards installed in the centre of MONA/MONB (Fig. 2) due to their greater depth, and with a ruler in other lakes. Evaporation rates were calculated from those measurements. All water samples were stored in 500 mL acid washed, plastic bottles in cool conditions prior to analysis. Sample pH and total dissolved solids (TDS) were measured using a TPS® conductivity-TDS-pH-temperature meter in the laboratory. Major cations and anions were measured at the Northern Territory Environmental Laboratories using standard methods: Ca, K, Mg, Na, SO_4 and SiO_2 (ICPOES), PO_4 (FIA), Cl (CL2) and HCO_3 and CO_3 (ALK1). Some samples were diluted to reduce matrix effects due to high TDS.

Table 1

Morphological characteristics of each study playa and piezometer data.

Site	Location (UTM)	Playa Length (m)	Playa Width (m)	Playa Area (ha)	Playa Shape Ratio*	Playa Orientation	Basal Elevation (masl)**	Piezo-meter name	Ground elevation (masl)	Depth (m)	No. of records	Comments
MONA	6731394 E 470977 N	237.6	129.3	2.3	0.52	NW-SE	271.9	A	272.36	1.52	3	
								B	272.345	1.54	3	
								C	272.463	1.28	2	submerged 17/06/03
								D	272.301	1.7	2	submerged 17/06/03
MONB	6730831 E 470970 N	183.1	203.6	2.8	1.0	ESE-WNW	270	A	271.189	1.24	2	
								B	271.203	1.09	2	
								C	271.17	1.09	2	
KA	6769926 E 446696 N	208.3	107.1	2.1	0.65	NNW-SSE	257.2	A	257.831	1.58	6	
								B	257.718	1.64	6	
								C	257.457	0.48	6	
								D	257.668	1.05	6	
								E	257.363	1	5	dry 16/06/03
								F	257.363	1.36	6	
								G	257.428	1.06	6	
								H	257.434	0.99	6	
								I	257.388	0.89	6	
KB	6769720 E 446638 N	148.8	89.3	1.05	0.78	NE-SW	258.9	A	258.87	1.57	3	
								B	258.828	1.93	3	
								C	258.904	1.79	3	
								D	258.901	1.92	3	
MA	6763562 E 403806 N	123.7	99.0	1.15	0.96	NNW-SSE	255.5	A	256.462	1.09	2	
								B	256.477	1.165	2	
								C	256.552	1.235	2	
								D	256.409	1.15	2	
MB	6764320 E 403795 N	167.4	94.4	0.93	0.42	NW-SE	256.8	A	255.294	1.7	3	
								B	255.372	1.68	3	
								C	255.348	1.6	3	
								D	255.245	1.02	3	

* The shape ratio: $S = A / (\pi(L/2)^2)$ compares the area of the shape (A) to the area of a circle with a diameter equal to the length of the longest axis (L) in the shape.
** masl = metres above sea level

Catchment inputs to surface water chemistry were not measured during the monitoring period due to a lack of opportunity to sample the short-lived stream flow events.

Groundwater measurements

Nested sets of piezometers were installed in the basin of each playa (Fig. 2) during dry phases in order to measure horizontal and vertical movement in the hydraulic head of the shallow ground waters. Each nest was surveyed relative to a Western Australian State Survey Mark using electronic surveying equipment to give an elevation relative to sea level. Piezometers were installed to a maximum depth of 2 m, which was deemed sufficient to capture variation in the depth to the water table, and the annulus was sealed with native sediments. Boggy conditions in sites MA and MONB prevented installation until late in the monitoring period and prevented the installation of any piezometers in the middle of MONB. Piezometer data are given in Table 1. Water table levels were measured and waters sampled approximately weekly during wet phases but otherwise irregularly. Groundwater chemistry was analysed following methods outlined for surface water samples. Point water heads were converted to freshwater hydraulic equivalents with a standard freshwater density of 1030 kg/m^3 to make variable densities comparable (Jacobson & Jankowski 1989; Jankowski & Jacobson 1989). Freshwater head equivalents were used in the ESRI Arc GIS 9.0 software package to interpolate hydraulic head contours (potentiometry). Interpolations were calculated within the software based on a nearest neighbour method and made using a regularised spline with an output cell size of 0.5 m. Interpolations and horizontal hydraulic gradient calculations were used to infer the direction of shallow groundwater flow lines. Vertical hydraulic heads were calculated at each piezometer nest and indicated on the potentiometric surface.

The groundwater monitoring regime was biased to wet phase records except in KA, with relatively few measurements due partly to time constraints on the project and conditions unfavourable to the timely installation of some piezometers. The network in MONB was reduced compared to other sites. This has implications for the interpolation of hydraulic head contours, which were based on a nearest neighbours technique and sensitive to the distribution of measured points. Also, while measurements were taken at approximately the same time of day, there may have been several centimetres of diurnal variation that was not measured.

Results

Surface water hydrology

Playas filled for the first time during the monitoring period in March 2003 and were monitored from this time until June 2004. Playa hydroperiods and filling frequencies were highly variable (Fig. 2a–c). In the absence of detailed monitoring and assuming that all water is lost by evaporation, average evaporation rates are given in Table 2 compared with Lake Eyre.

Mongers A and Mongers B

Hydroperiod

MONA had three hydroperiods lasting 44, 84 and 33 days with a maximum depth of 450 mm (Fig. 2a). Monitoring ceased before the end of the fourth hydroperiod that started in early April 2004. MONB held water for the longest period of at least 211 days from early May to early December 2003, reaching a maximum depth of 1000 mm. Monitoring ceased in mid-June 2004 before the end of the second cycle that started in early March 2004. MONA filled from dry to 70 mm depth and MONB increased in depth by 640 mm following 13 mm of rainfall (Fig. 2d) over four days, recorded at the nearby Wanarra station homestead located approximately 5km to the NE during July 2003. Water levels were maintained at 700 – 800 mm for 114 days by numerous small rainfall events of less than 17 mm. A major rainfall event of 80 mm filled MONA and MONB from dry to 160 and 800 mm depth, respectively, during March 2004.

Catchment analysis

On-ground observations and visual interpretation of the aerial photography show that MONA and MONB are open basins in terms of surface flow (Fig. 3a). GIS analysis of drainage lines showed that both playas are part of a connected drainage network that empties into Lake Monger, however, the Wanarra road may have

Table 2

Mean evaporation rates and salinity based on weekly lake depth measurements of surface water, and depth and range of shallow groundwater table for each playa. Lake Eyre figures from (Bonython, 1955 and Tetzlaff and Bye, 1978).

Playa	Mean evaporation rate (mm/day)	Mean TDS (g/L)	Mean depth to groundwater (m)**	Groundwater depth range (m)
MONA	5.0	62.6	0.41	0 – 1.44
MONB*	7.8	12.7	0.0	0 – 0.28
KA	0.5	14.15	0.59	0 – 1.15
KB	0.4	34.1	1.05	0.78 – 1.08
MA	6.7	122.5	0.38	0 – 0.66
MB	1.9	185.0	0.36	0 – 1.75
Lake Eyre	4.9–5.8	–	–	–

* not in middle / no dry phase readings

** measurements taken on same dates as groundwater samples (see Table 3)

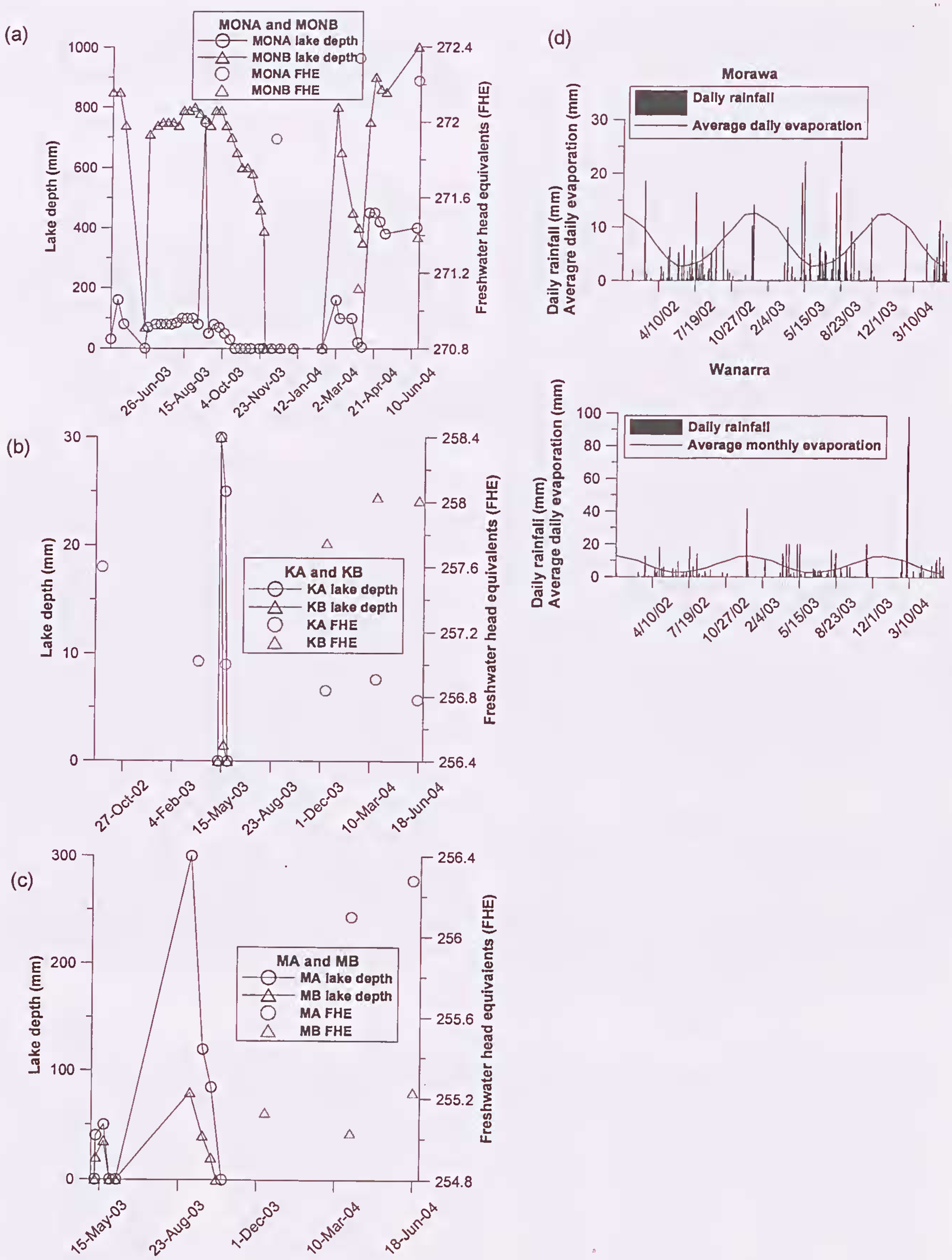

Figure 2. The hydroperiod and average freshwater head equivalents of (a) MONA and MONB; (b) KA and KB; and (c) MA and MB during the monitoring period. Rainfall data from the Morawa townsite records (Bureau of Meteorology, 2004) for Kadji and Morawa sites and from Wanarra landowner records for Mongers sites (d).

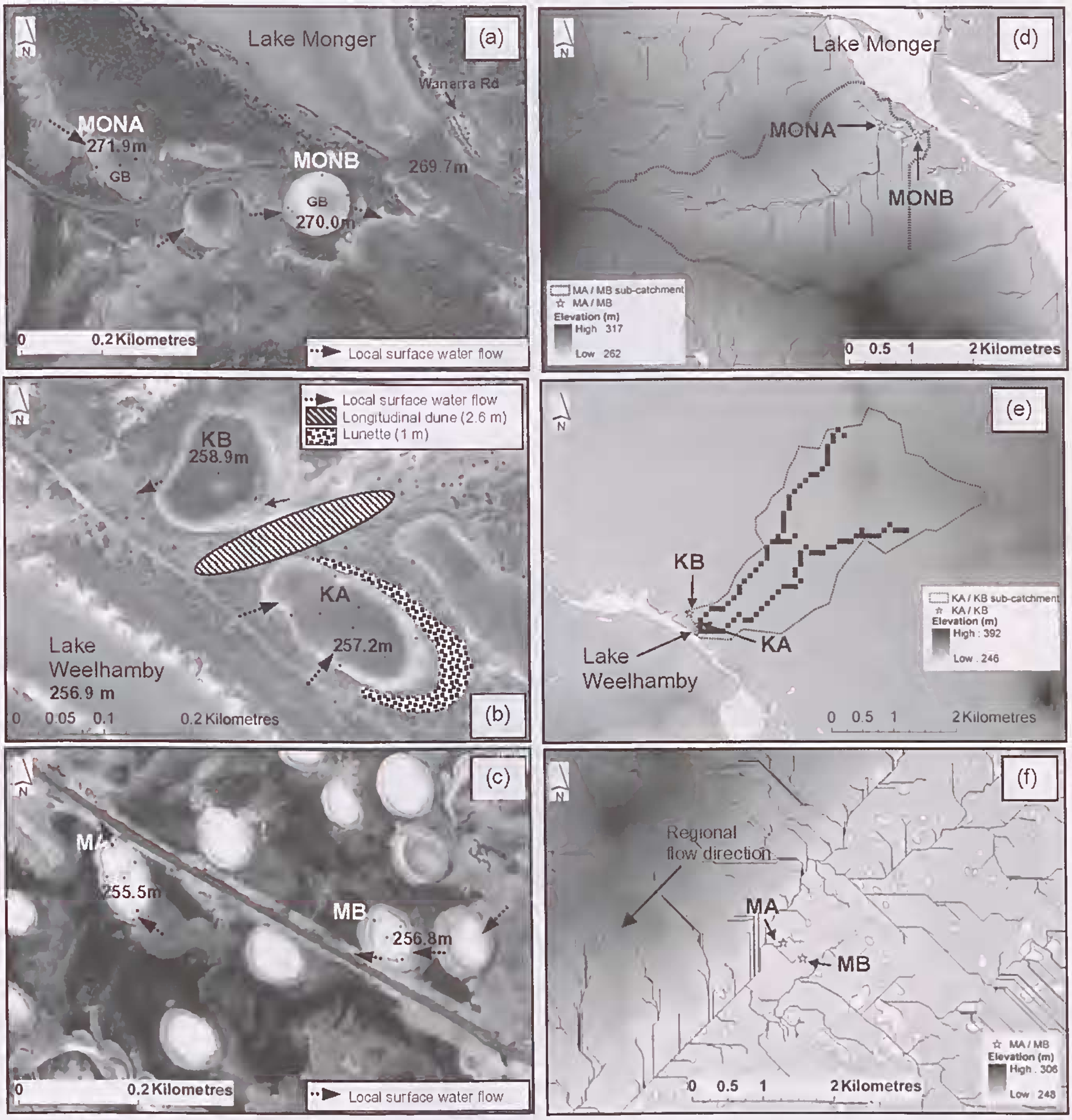

Figure 3. The study playas; (a) Mongers A and B (MONA/MONB), (b) Kadji A and B (KA/KB), and (c) Morawa A and B (MA/MB) showing the location of piezometers and gauge boards (GB), basal elevations and the direction of local surface water flow. GIS derived elevations, sub-catchments and drainage lines of each pair of playas; (d) Mongers, (e) Kadji and (f) Morawa (no catchment defined)

interrupted connection between playas on either side of the road (Figures 3a and 3d). The GIS analysis defined a sub-catchment area of 1043.6 hectares with a mean slope of 1.4% (min: 0%; max: 5.1%; S.D. 0.8%) (Fig. 3d).

Kadji A and Kadji B

Hydroperiod

KA and KB had the shortest hydroperiods, containing 30 mm depth of water or less for a maximum of 19 days during March 2003 following an 18.2 mm rainfall event at Morawa (Fig. 3b).

Catchment analysis

On-ground observations and visual interpretation of the aerial photography show that KA and KB are part of separate surface flow networks (Fig. 3b). KA it is a terminal basin for a small local catchment area, separated from the regional surface flows by its bounding dunes. It is bound on the east and south by a 1m high lunette and separated from KB by a 2.6 m high longitudinal dune. It does not have an obvious outflow to the Weelhamby playa but has two small inlets on the west shore, delivering run-off generated from the road (Fig. 3b). In contrast KB is an open basin, connected to the regional

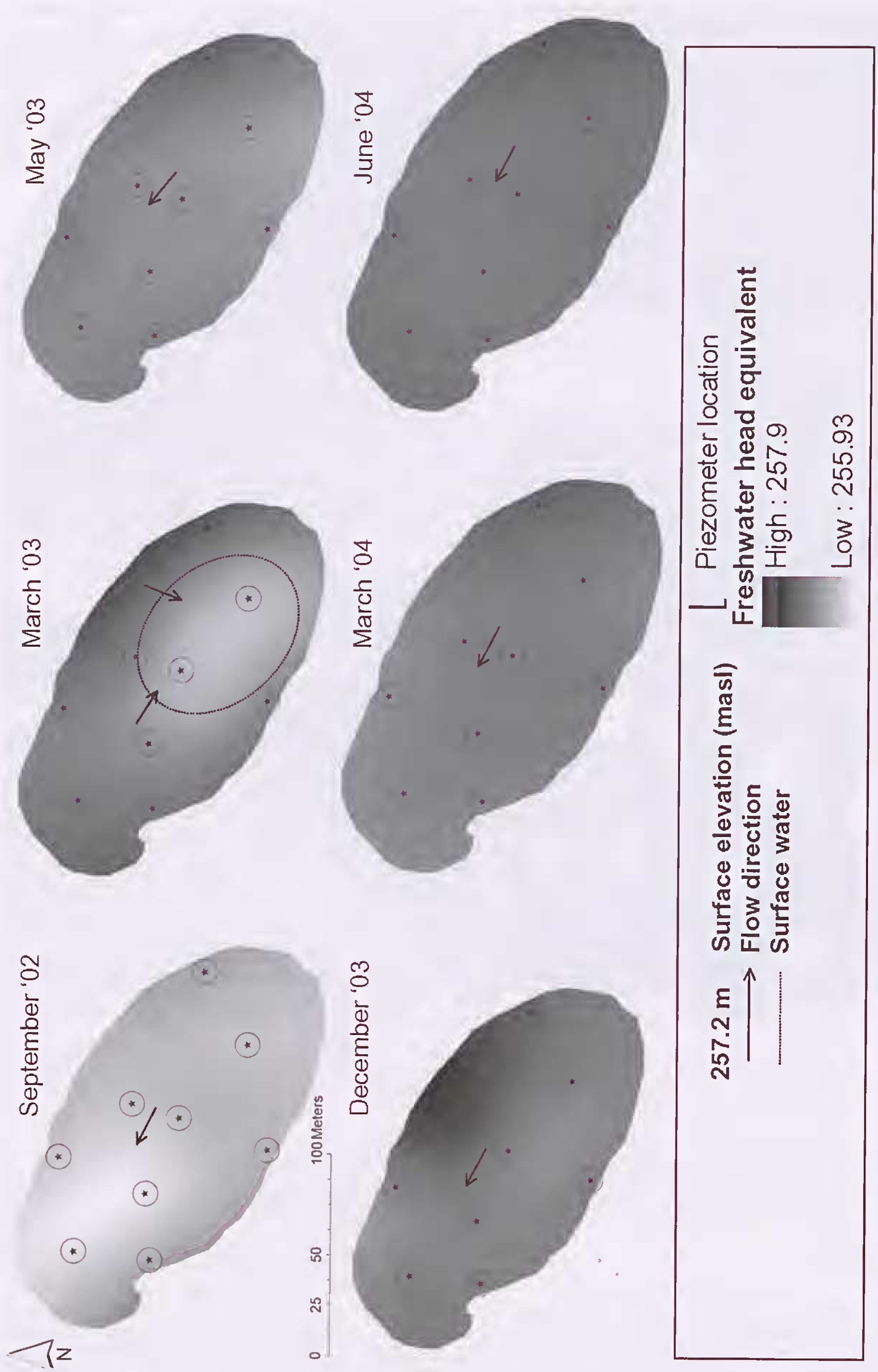

Figure 4. Potentiometric head and groundwater flow directions over time in Kadji A.

drainage which originates in the north-west through an inlet on the east shore with an over-flow to the Weelhamby playa through an outlet on the east shore (Fig. 3b). GIS analysis of the DEM defined a sub-catchment area of 733.86 ha with a mean slope of 1.3% (min 0%; max 6%; S.D. 1.08) (Fig. 3e). The sub-catchment originates at a steep ridge in the east but otherwise has a low slope of < 1.5%. The 3 second DEM generated a connected drainage network which terminated in KA (Fig. 3e). This does not reflect accurately on-ground

Table 3

Ionic composition, salinity and pH of surface water samples.

Sample #	Lake	Date	Concentration of major ions (g/L)								pH
			Na^+	Mg^{2+}	Ca^{2+}	K^+	Cl^-	SO_4^{2-}	alk	TDS	
1	KA	10/05/2003	1.7	0.2	0.7	0.1	3.0	1.9	0.1	7.6	7.2
2	KA	20/05/2003	5.2	0.5	1.2	0.3	10.0	3.1	0.0	20.3	8.3
3	KB	10/05/2003	4.9	0.4	0.9	0.3	8.7	2.3	0.1	17.5	7.0
4	KB	20/05/2003	12.8	1.9	1.4	0.5	33.1	5.8	0.2	55.7	7.8
5	MA	10/05/2003	19.0	1.6	1.1	0.6	9.4	4.1	0.1	35.8	7.1
6	MA	20/05/2003	26.6	2.5	1.3	0.7	40.2	6.4	0.0	77.7	8.3
7	MA	28/05/2003	60.2	6.0	1.0	1.5	120.7	11.1	0.1	200.6	8.1
8	MA	7/09/2003	17.3	1.8	0.8	0.4	33.1	4.4	0.1	58.0	7.2
9	MA	23/09/2003	26.8	2.8	1.4	0.7	51.0	7.0	0.1	89.8	7.5
10	MA	4/10/2003	44.3	4.8	1.3	1.2	83.7	9.9	0.2	145.4	7.4
11	MA	17/06/2004	74.0	8.1	0.8	1.8	141.0	15.6	0.1	241.3	7.1
12	MB	10/05/2003	22.1	2.0	1.4	0.6	31.8	5.6	0.1	63.7	6.6
13	MB	20/05/2003	25.1	2.6	1.6	0.7	48.0	7.2	0.1	85.2	7.8
14	MB	7/09/2003	44.2	3.8	1.3	1.3	87.9	8.7	0.1	147.3	7.0
15	MB	23/09/2003	72.0	6.6	0.9	2.0	136.1	12.1	0.2	229.8	7.3
16	MB	4/10/2003	94.9	14.2	0.3	3.9	187.7	23.8	0.3	325.1	7.3
17	MB	17/06/2004	97.0	11.1	0.4	3.0	168.9	18.9	0.1	299.4	6.6
18	MONA	11/05/2003	8.6	0.9	0.8	0.3	15.0	2.4	0.1	28.1	8.6
19	MONA	20/05/2003	6.3	0.6	0.5	0.2	10.8	1.7	0.1	20.3	8.8
20	MONA	27/05/2003	7.9	0.8	0.7	0.3	20.7	2.1	0.1	32.6	8.9
21	MONA	10/06/2003	11.3	1.2	0.9	0.4	15.3	2.8	0.1	31.8	8.8
22	MONA	12/07/2003	17.3	2.0	1.3	0.7	34.6	4.7	0.1	60.6	7.3
23	MONA	26/07/2003	24.7	2.9	1.6	0.9	53.1	6.2	0.1	89.4	7.0
24	MONA	9/08/2003	38.2	4.7	1.6	1.3	76.6	8.2	0.2	130.9	7.0
25	MONA	30/08/2003	19.8	2.4	1.1	0.7	39.9	4.8	0.1	68.7	7.1
26	MONA	7/09/2003	24.4	3.0	1.6	0.8	45.3	6.4	0.2	81.6	7.2
27	MONA	23/09/2003	47.0	6.1	1.3	1.5	90.6	9.1	0.3	155.9	7.1
28	MONA	23/03/2004	7.9	0.9	0.7	0.3	14.7	2.4	0.1	27.1	7.3
29	MONA	31/03/2004	21.6	2.6	1.5	0.9	42.0	5.8	0.1	74.4	7.9
30	MONA	5/04/2004	46.4	6.1	1.5	1.7	91.9	9.2	0.2	156.9	7.4
31	MONA	14/04/2004	0.4	0.0	0.0	0.0	0.9	0.1	0.0	1.5	7.4
32	MONA	21/04/2004	2.2	0.2	0.2	0.1	4.7	0.6	0.1	8.1	7.6
33	MONA	28/04/2004	2.7	0.3	0.2	0.1	5.9	0.7	0.1	10.0	7.5
34	MONA	4/05/2004	3.3	0.4	0.2	0.1	7.6	0.8	0.1	12.6	7.8
35	MONA	16/06/2004	3.9	0.4	0.2	0.2	8.2	0.9	0.1	13.9	9.0
36	MONB	11/05/2003	1.8	0.2	0.1	0.1	3.7	0.5	0.1	6.5	8.1
37	MONB	20/05/2003	1.8	0.2	0.1	0.1	3.8	0.5	0.1	6.7	8.7
38	MONB	27/05/2003	2.0	0.2	0.1	0.1	3.8	0.6	0.1	7.0	9.1
39	MONB	18/06/2003	2.2	0.2	0.1	0.1	3.9	0.6	0.1	7.3	9.7
40	MONB	12/07/2003	2.6	0.3	0.2	0.1	5.4	0.7	0.1	9.2	8.9
41	MONB	26/07/2003	2.8	0.3	0.2	0.1	5.5	0.7	0.1	9.6	9.5
42	MONB	9/08/2003	3.0	0.3	0.2	0.1	5.5	0.7	0.1	9.9	9.3
43	MONB	30/08/2003	3.1	0.3	0.2	0.1	6.3	0.8	0.1	10.9	9.4
44	MONB	7/09/2003	3.3	0.4	0.2	0.1	6.7	0.8	0.1	11.5	9.5
45	MONB	23/09/2003	3.7	0.4	0.2	0.1	7.1	0.9	0.1	12.5	9.7
46	MONB	4/10/2003	4.3	0.5	0.2	0.2	9.0	1.0	0.1	15.3	9.3
47	MONB	19/10/2003	5.3	0.6	0.3	0.2	10.3	1.2	0.1	17.9	8.7
48	MONB	30/11/2003	20.7	2.5	0.8	0.8	42.2	4.6	0.1	71.7	6.8
49	MONB	23/03/2004	2.0	0.2	0.2	0.1	3.4	0.6	0.1	6.6	7.8
50	MONB	31/03/2004	3.1	0.4	0.2	0.1	6.7	0.9	0.1	11.6	7.8
51	MONB	5/04/2004	3.7	0.4	0.3	0.2	7.1	1.1	0.1	12.9	8.3
52	MONB	14/04/2004	1.4	0.2	0.1	0.1	2.9	0.4	0.0	5.1	7.3
53	MONB	21/04/2004	1.9	0.2	0.1	0.1	3.4	0.5	0.1	6.3	8.8
54	MONB	28/04/2004	2.1	0.2	0.1	0.1	3.4	0.5	0.1	6.5	8.9
55	MONB	4/05/2004	2.4	0.3	0.1	0.1	4.8	0.6	0.1	8.3	8.2
56	MONB	16/06/2004	2.3	0.3	0.1	0.1	4.8	0.5	0.1	8.3	9.6

conditions, suggesting that resolution of the DEM was too coarse to detect the local dune topography which appears to be important in directing surface runoff.

Morawa A and Morawa B

Hydroperiod

MA and MB had two complete inundation cycles during 2003, one in May and one in July / August with hydroperiods of less than 45 days with a maximum depth of 300 and 80 mm in each playa respectively (Fig. 2c). The playas held water following a rainfall event of 18.2 mm recorded at Morawa during May, then dried out and re-filled following eight consecutive days of small events (measuring 0.6 – 6.6 mm) totalling 18.8 mm in July 2003.

Catchment analysis

On-ground observations and visual interpretation of the aerial photography show that MA and MB are open basins in terms of surface flow, with one inlet and one outlet (Fig. 3c). GIS analysis of drainage lines show that they are part of a regional drainage system that flows to the south-west. The playa sub-catchments could not be defined using the DEM due to the flat topography thus they are part of the regional catchment for the entire palaeodrainage in this area (Fig. 3f). This makes them different from KA/KB and MONA/MONB which have local sub-catchments and is related to the geomorphological origins of the playas.

Groundwater hydrology

KB had on average the deepest water table while the MONA water table was on average, present at the surface (Table 2). The shallow ground water suggests that the playas are likely to be net discharge points for ground water during dry phases. However, small, local vertical head gradient variations indicate that groundwater is not discharging at the same rate across the playa surface. In all playas, temporary zones of recharge occurred when surface water was present. For example, MONB during the dry period of December '03 was in a discharge phase compared with a recharge phase recorded during the significant wet period in June following year. This shift coincided with a change in flow direction from NW to SE (downstream).

The potentiometry of KA derived from the GIS interpolation is given as an example in Figure 4, with general directions of shallow groundwater flow and vertical hydraulic gradients indicated. The water table is horizontal and horizontal hydraulic gradients are small, for example ranging from 0.002 – 0.0002 in March '03. However, the lateral and vertical direction of local, shallow groundwater flow is not temporally consistent. For example, lateral flow in September '02 was towards the NW (downstream). At this time the lake was primarily in a discharge phase, compared to the following year in March during a minor wet phase when flow into central recharge zone.

Hydrochemistry

pH and TDS

Surface waters varied more widely in pH (6.6 – 8.9) and TDS (1.5 – 325 g/L) (Table 3) than groundwater samples. Ground waters (Table 4) had a small pH range of 6.5 – 7.5. TDS ranged between 118 – 326 g/L except in three samples (12–14) where TDS was < 77 g/L.

pH decreased with increasing salinity in both ground and surface waters. pH increased with maximum depth in surface waters while TDS decreased with maximum depth (Fig. 5). MONB consistently had the lowest salinity and highest pH throughout the monitoring period due to its relatively deep surface water.

Table 4

Ionic composition, salinity, density and pH of ground water samples.

Sample #	Lake	Date	Concentration of major ions (g/L)									
			Na^+	Mg^{2+}	Ca^{2+}	K^+	Cl^-	SO_4^{2-}	alk	TDS	Density (kg/m^3)	pH
1	KA	10/05/2003	69.5	8.8	0.8	2.5	117.6	14.1	0.1	213.3	1169.0	6.8
2	KA	20/05/2003	68.5	8.6	0.8	2.4	123.0	14.2	0.1	217.5	1172.6	7.0
3	KA	28/05/2003	68.5	8.6	0.8	2.4	127.2	14.1	0.1	221.6	1176.3	7.0
4	KA	12/12/2003	69.8	9.0	0.7	2.4	131.7	17.5	0.1	231.2	1184.7	6.9
5	KA	23/03/2004	72.2	9.1	0.7	2.5	147.3	17.6	0.1	249.6	1201.2	7.0
6	KA	16/06/2004	66.6	8.9	0.8	2.3	129.2	17.0	0.1	224.8	1179.0	7.0
7	KB	12/12/2003	75.0	10.7	0.6	2.9	145.2	19.1	0.1	253.6	1204.8	6.6
8	KB	23/03/2004	74.4	10.9	0.6	3.0	144.7	20.2	0.1	253.8	1205.0	6.9
9	KB	16/06/2004	74.4	10.8	0.5	2.9	146.4	19.7	0.1	254.7	1205.9	6.8
10	MA	30/03/2004	84.1	9.5	0.6	1.9	154.8	17.1	0.1	268.0	1218.0	6.7
11	MA	17/06/2004	48.1	4.8	1.0	1.2	91.9	10.0	0.1	157.1	1121.0	7.0
12	MB	12/12/2003	90.4	13.1	0.4	3.1	177.9	22.1	0.4	307.4	1254.7	6.8
13	MB	23/03/2004	35.0	4.8	0.6	1.1	69.0	7.7	0.1	118.2	1089.0	7.0
14	MB	30/03/2004	94.9	14.5	0.3	3.6	186.3	25.2	0.3	325.1	1271.6	7.0
15	MB	17/06/2004	94.5	6.6	0.7	2.3	177.5	12.3	0.2	294.1	1242.1	6.7
16	MONA	12/12/2003	61.6	9.0	0.7	1.9	118.7	13.1	0.1	205.0	1161.7	6.5
17	MONA	31/03/2004	41.6	5.6	0.7	1.3	79.7	8.8	0.1	137.7	1104.9	6.9
18	MONA	16/06/2004	22.7	2.5	0.6	0.9	45.9	4.2	0.1	76.8	1056.1	7.5
19	MONB	31/03/2004	19.6	2.0	0.5	0.8	40.1	3.7	0.2	66.8	1048.3	6.9
20	MONB	16/06/2004	8.5	1.0	0.3	0.3	17.4	1.6	0.1	29.2	1019.6	6.6

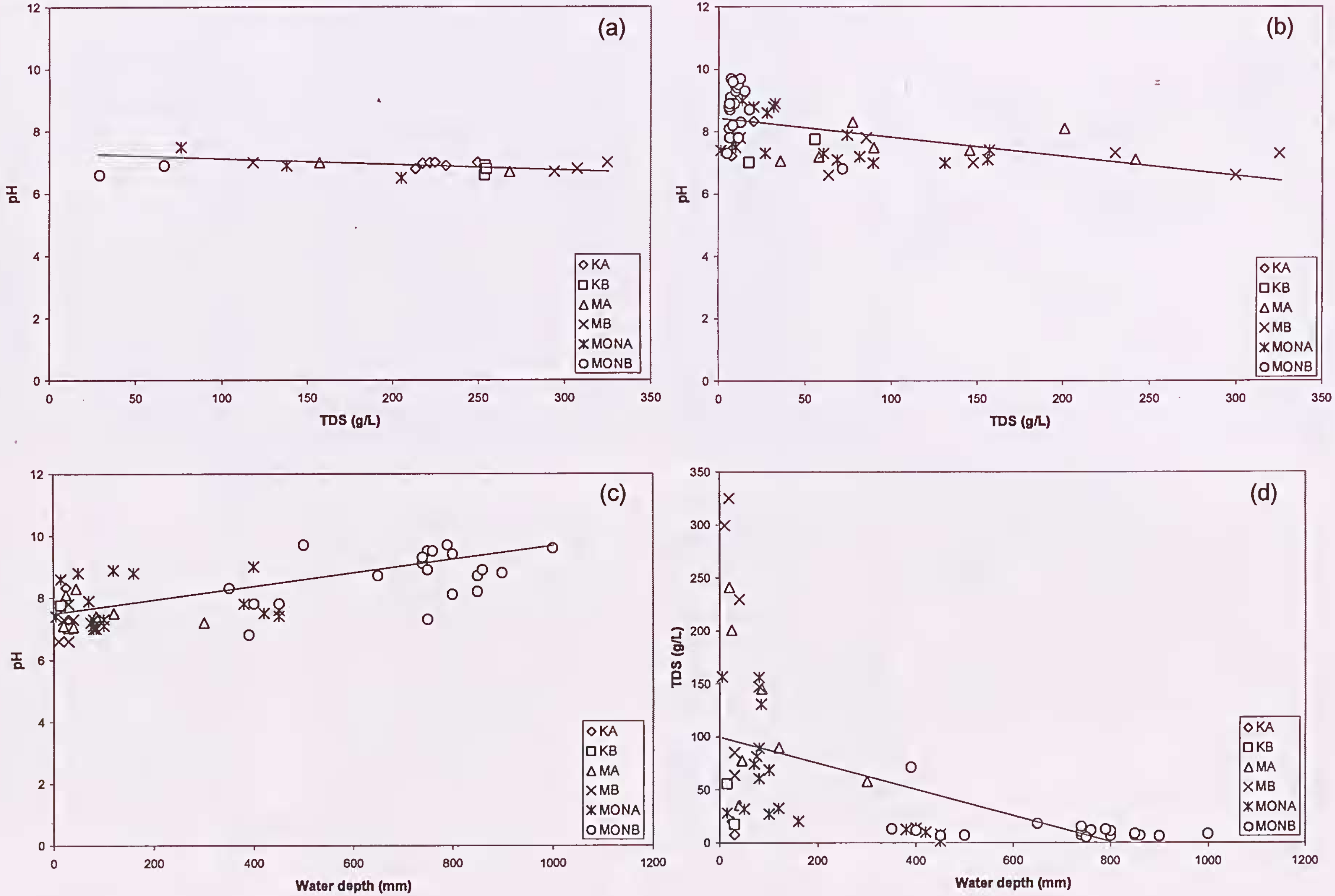

Figure 5. The relationship between pH and TDS in (a) groundwater, (b) surface waters and pH and TDS relationships to surface water depth (c & d respectively).

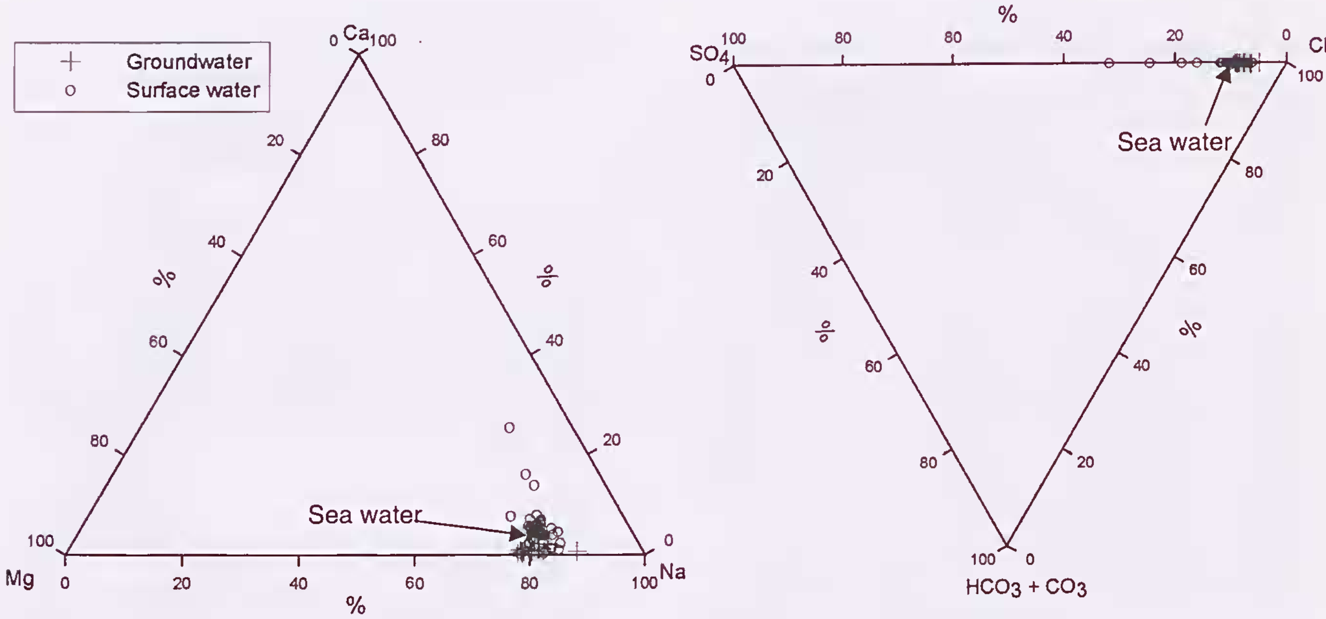

Figure 6. Ternary diagrams showing the relative proportion on ions in surface water and groundwater samples compared to sea water.

Eight ground water and surface water samples were taken synchronously. Surface samples were less saline than corresponding ground waters except in MA and MB. The correlation value between the TDS of the two waters was 0.33, however, it increased to 0.84 with the exclusion of samples from KA (10/05/03; 20/05/03), which had the greatest gradient of TDS between surface and ground waters.

Ionic analyses

Ionic analysis of the ground water samples showed a consistent pattern of ionic dominance: $Na^{+} > Mg^{2+} > K^{+} > Ca^{2+}$: $Cl^{-} > SO_4^{2-} > HCO^{3-} > CO_3^{2-}$ (Table 5). Using the Eugster & Hardie (1978) method of nomenclature for comparing brine types, the ground waters are type Na-(Mg)-Cl-(SO4) (Table 5). The relative proportions of major solutes in groundwater samples did not vary remarkably between playas as shown in the ternary plots (Fig. 6). The plots are consistent with saline ground waters elsewhere in Western Australia which are dominated by Na and Cl ions.

Similarly, playa surface waters were dominated by Na and Cl (Fig. 6); however, they showed a slightly more varied ionic dominance than the groundwater samples. The majority of samples had a pattern of ionic dominance consistent with that typical of sea water: $Na^{+} > Mg^{2+} > Ca^{2+} > K^{+}$: $Cl^{-} > SO_4^{2-} > HCO^{3-} > CO_3^{2-}$ (Table 5). However seven samples deviated from this pattern being either enriched (samples 1, 2, 9) or comparatively depleted in Ca^{2+} (samples 53–56) to resemble ground waters (Table 5).

The relationships between ionic ratios and salinity in all water samples are shown in Figure 7. They are similar to those described by Jankowski and Jacobson (1989) who investigated the evolution of regional fresh groundwater inflow to saline ground water brines in playas of central Australia. We propose that shallow ground water brines sampled in this study have evolved *via* a geochemical pathway similar to the 1B pathway described by Jankowski and Jacobson (1989). The pathway is illustrated in Figure 8 and related to playa physical hydrology. The three phases of a hydroperiod, namely flooding, evaporative concentration and desiccation are accompanied by three brine types of varying composition: the initial composition, in this case the composition of rainwater in the vicinity of the Yarra Yarra drainage system after Hingston & Gailitis (1976);

Table 5

Brine classification of surface waters and ground waters (parentheses) compared to sea water.

Pattern of ionic dominance	Sample (refer Table 3 and 4))
Na>Ca>Mg>K : $Cl>SO_4>HCO_3>CO_3$	1,2,9
Na>Mg>Ca>K : $Cl>SO_4>HCO_3>CO_3$	3-8, 10-52; seawater
Na>Mg>K>Ca : $Cl>SO_4>HCO_3>CO_3$	53-56; (1-20)
Eugster and Hardie	
Na-(Ca)-(Mg)-Cl-SO_4	1
Na-(Ca)-(Mg)-Cl-(SO_4)	2,9
Na-(Mg)-(Ca)-Cl-(SO_4)	3-8, 10-15, 17-19, 22, 24 26-39, 41-50; seawater
Na-(Mg)-Cl-(SO_4)	16, 20, 21, 23, 25, 37-40, 51-56; (1-20)

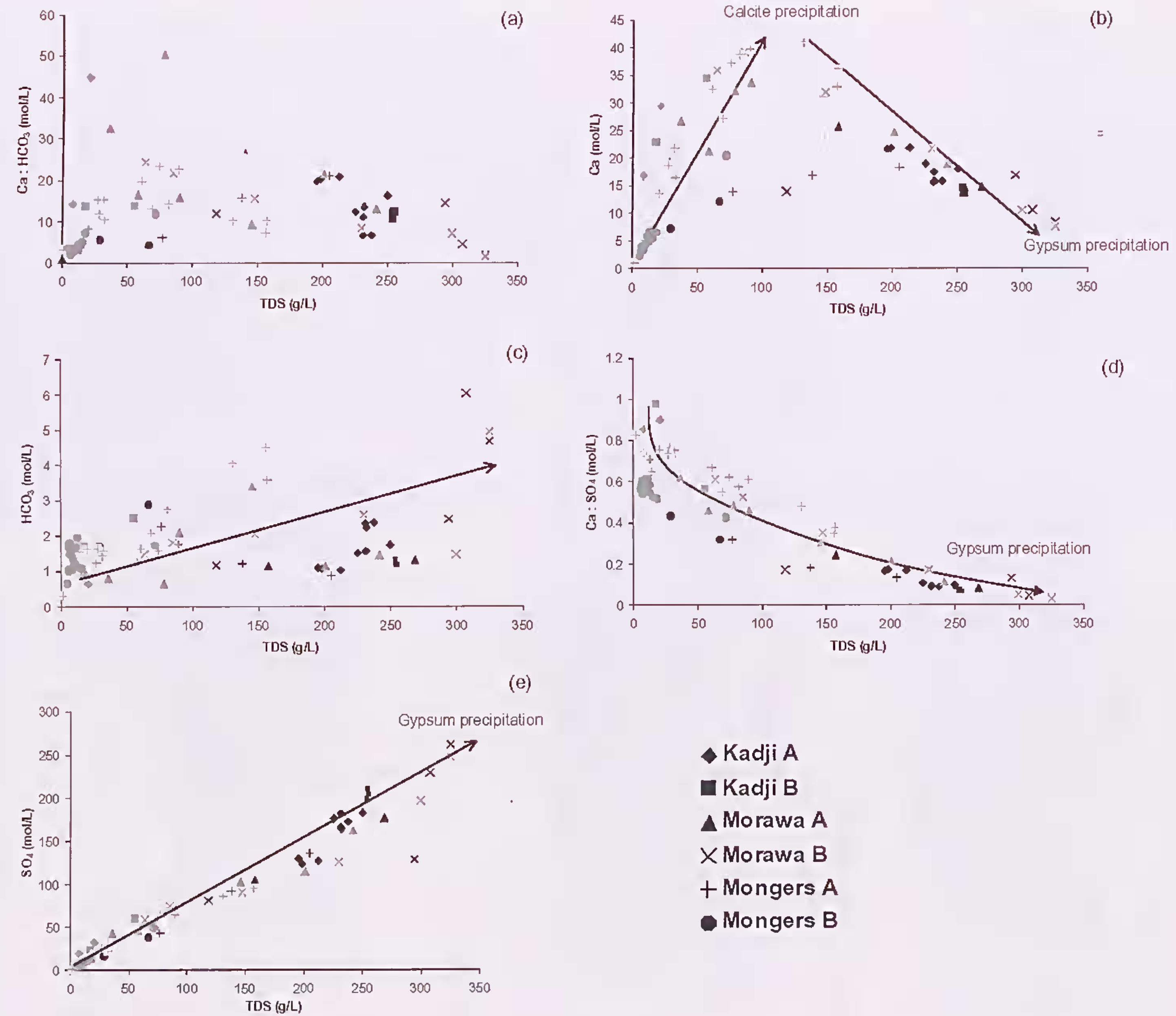

Figure 7. (a) Ca: HCO_3 ratio and (b) Ca and (c) HCO_3 concentration relationship to salinity in ground waters (black symbols) and surface waters (grey symbols); (d) Ca: SO_4 ratio and (e) SO_4 concentration relationship to salinity in ground waters (black symbols) and surface waters (grey symbols). Arrows identify the direction of mineral precipitation.

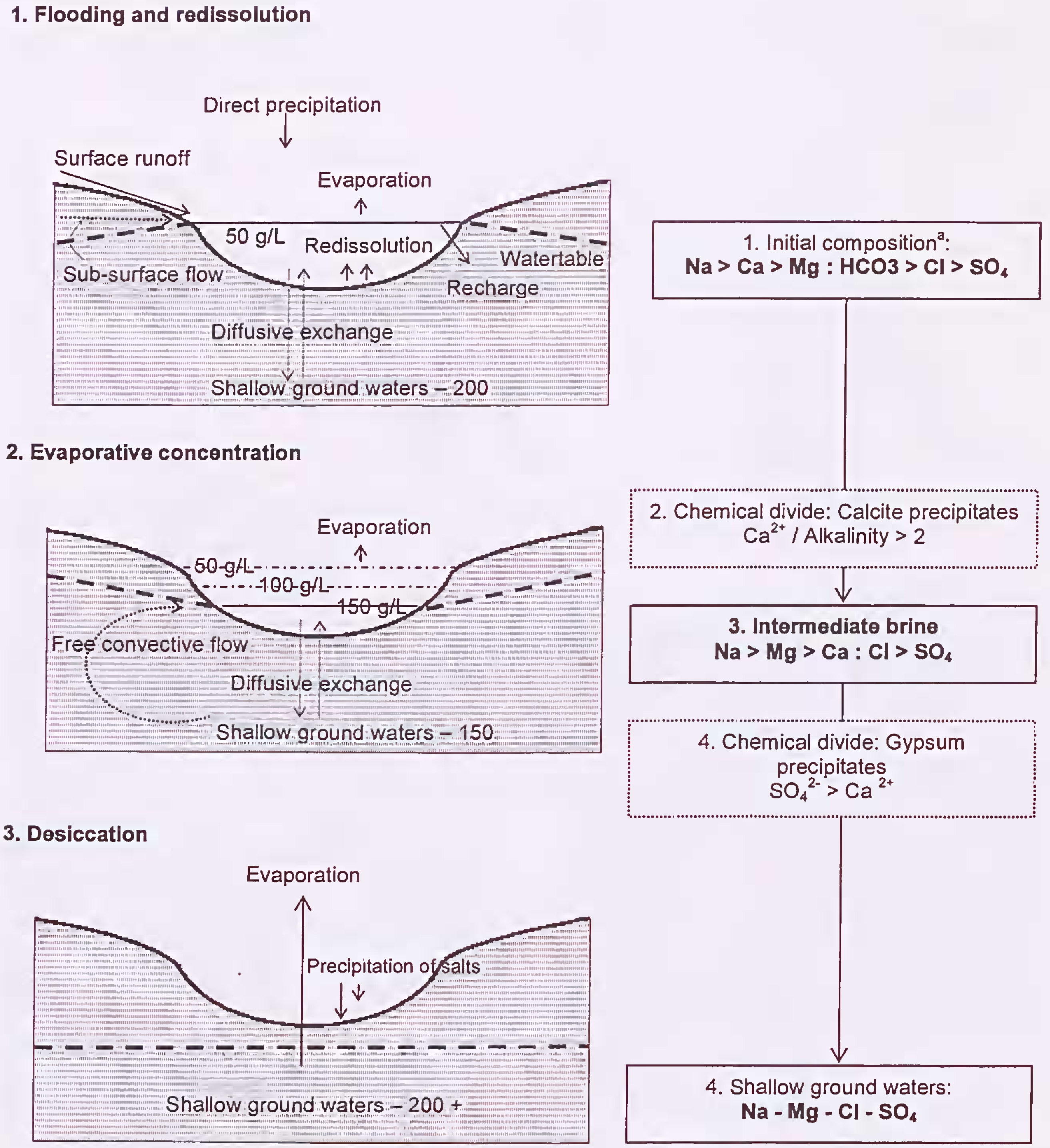

Figure 8. Potential pathway for brine evolution based on 1B pathway of Jankowski and Jacobson (1989), in relation to the physical hydrology of the playas modified from Shaw & Thomas (1989) and Fan *et al.*, 1997. [a] Initial composition derived from Hingston & Gailitis (1976).

the intermediate brine that persists after the first chemical divide where calcite precipitates; and the resulting shallow groundwater brine that evolves after the second chemical divide where gypsum precipitates.

Discussion

As ephemeral lakes, the playas studied here display a combination of characteristics and processes common to both permanent and permanently dry lake types. We discuss the results of the research in three parts: factors influencing the mechanics of surface water hydrology; the hydrology of shallow groundwater; and processes defining the hydrochemical character of the playas.

Surface water hydrology

The playas represent a combination of stages C and D in Bowler's (1986) continuum of lake basins. During the monitoring period, the continuum was exemplified through MONB at the 'C end' (most often wet) and KA at the 'D end' (most often dry). Collectively they are ephemeral basins and therefore alternate between two distinct hydrological phases; *the wet phase* of variable length and salinity, comprised of three internal hydrochemical phases of i. inundation, ii. evaporation and iii. desiccation; and *the dry phase* consisting of variable drought periods in which playas are primarily groundwater-dominated or discharge playas (Fig. 8). Geomorphically the 6 playas are similar in that they are elliptical to circular and shallow (< 1 m). According to Bowler's continuum, KA should have an irregular outline if it is a true groundwater dominated playa, however its smooth shorelines may be an inherited feature from past high rainfall periods. Thus the morphology of the lake is not necessarily reflecting the current hydrologic environment.

The frequency and duration of filling events in playas of the Yarra Yarra system is controlled in part by rainfall distribution across the catchment reflecting rainfall patchiness and variable catchment characteristics. The progressive SW to NE pattern of decreasing average rainfall is likely to produce variable spatial and temporal patterns in playa filling frequency and hydroperiod, although this has not been investigated systematically and remains the subject of further work in the catchment. In addition, the downstream topographic gradient along the drainage line is variable. Low gradient stretches in the system, for example the southern section of Lake Monger and the 40 km stretch south of Lake Nullewa (see Fig. 6 Boggs *et al.* 2006), may act as surface water sinks further influencing the distribution and residence time of surface water.

Detailed analysis of filling frequency and hydroperiod using remotely sensed data has been performed on other Australian salt lake systems (Turner *et al.* 1996; Roshier *et al.* 2001). Roshier *et al.* (2001) identified that three successive months of 20 mm rainfall was a sufficient threshold for filling playas in arid Australia. We identified that an event or a series of events totalling 18.8 mm triggered a filling event in all playas investigated. However, such events did not *always* result in a filling event in all lakes, suggesting that factors other than rainfall, *e.g.* drainage connectivity, contribute to playas filling. For example, MA/MB and MONA/MONB are located in similar average rainfall zones (Fig. 1) but had very different filling regimes. This could be attributed mostly to the variability in rainfall between the two sites during the monitoring period (Fig. 3c), however they also have markedly different catchment characteristics. The sub-catchment derived for MONA/MONB appears to be effective in generating run-off, *i.e.* high slope with strongly connected drainage channelling creek water directly into the playas. In comparison, MA/MB are part of a very flat, large regional catchment with comparatively poorly connected drainage network. For KA/KB the rainfall record taken at Morawa may be too far away to reflect accurately the rainfall in the sub-catchment. Being in a low rainfall zone, it was not unexpected that KA/KB had very little surface water during the monitoring period. KA, in particular, rarely is likely to accumulate appreciable surface water given that it is separated from the sub-catchment drainage by dunes.

In all playas, the pre-condition of the catchment will play a significant role in the amount of run-off and/or subsurface flow that enters the basin. Factors including the soil saturation and resultant runoff and/or seepage from the capillary fringe as well as the catchments efficiency in delivering run-off to the playas will contribute to the amount of water entering the basin.

The evaporation rates for each lake do not necessarily reflect the inverse relationship between evaporation rate and surface water salinity that is often recorded in saline water bodies (Drever 1982; Kotwicki 1986; Yechieli & Wood 2002). The evaporation rates recorded vary widely, suggesting that loss is occurring through avenues other than direct evaporation. For example, the rates for MONA/MONB are likely to be high; the playas undoubtedly lost surface water downstream to the Mongers playa through the surface water outlet (Fig. 2c).

Groundwater hydrology

Regional groundwater flow in the Yarra Yarra drainage system is towards the playas, which are topographical low points, and inferred local discharge points for groundwater (Commander & McGowan 1991). Therefore, simplistically, regional recharge flows into the playas and leaves *via* evaporation from the playa floors. However, we have presented some evidence here of more variable patterns of local groundwater movement that respond to the presence of surface water. The playas probably recharge to the unsaturated zone between the lake bed and the water table during wet phases. Unlike some playa systems further inland, such as those in the Eastern Goldfields of Western Australia, the Yarra Yarra lakes receive relatively regular runoff and are therefore likely to recharge annually through their basin floors or through permeable basin margins. Recharge may also be occurring outside the basins in porous dune areas and adjacent calcrete deposits (Commander & McGowan 1991) and enter the playas as relatively fresh sub-surface flow.

The playas are not likely to be hydrologically closed but through-flow playas and part of a regional groundwater flow system supported by the consistent chemistry of their local groundwater. Given that regional lateral groundwater flow is catchment controlled, then movement will be very slow as the average topographic gradient along the lowest part of the salt lake valley between Lake Monger and Yarra Yarra is less than 0.0005% or a total decline of only 52 m over 270 km (Boggs *et al.* 2006).

Variations in the position of the water table relative to the elevation of the basin may be significant to the hydrochemistry of the playas through the relative contribution of recharge waters (Shaw & Thomas 1989) and the preservation of salts, *i.e.* the development of evaporative crusts. Jacobson and Jankowski (1989) in their investigation of central Australian playas found that adjacent playas at different elevations (*e.g.* Glauberite Lake compared to more elevated Lake Amadeus) are differentially affected by groundwater. The 6 playas investigated here have variable elevations and positions in the landscape relative to other playas that might influence their hydrological characteristics (see Fig. 2). KA/KB and MONA/MONB have evolved peripherally to large adjacent playas (Weelhamby and Mongers respectively) while MA/MB are located within the main palaeodrainage and probably segmented remnants of a larger playa in this area. Here the playas are known to develop thick evaporative crusts, this combined with the flat topography and poorly connected surface drainage suggests that playas are likely to be strongly influenced by shallow ground waters. The similarity of surface water and groundwater salinity in MA/MB supports this proposition.

Hydrochemistry

The small playas investigated did not show any unique chemical characteristics during the monitoring period but were consistent with previous hydrochemical research undertaken on playas in Yarra Yarra catchment (Geddes *et al.* 1981; Brock & Lane 1983; Cruse *et al.* 1989; Regeneration Technology 2001; Smith 2001) and with the major reviews of Australian salt lake chemistry (Williams 1967; Buckney 1980; Geddes *et al.* 1981; DeDeckker 1983). The results therefore supported the theory that playa salts are derived from marine aerosols (Chivas *et al.* 1991).

We were able to identify the progressive evaporative concentration of salts (stage 2, Fig. 8) in the water depth to salinity relationship. pH values showed a weak inverse relationship to salinity and therefore water depth, however, the relatively circum neutral pH of both ground waters and surface waters reflects the buffering capacity of Na and Cl as described by Gasse (1986).

Except in MA and MB, the ground waters were less saline than surface waters, indicating that evaporation was proceeding more slowly than diffusive exchange; thus, with progressive evaporation, diffusive flux between the surface and shallow ground waters progressively reduced the concentration gradient between the waters so that they became chemically more similar with time until the playas dried. Long periods of dry such as in KA will produce highly evolved shallow ground waters, *i.e.* strongly dominated by Na and Cl. In contrast, long periods of wet such as in MONA, halt brine evolution (Yechieli & Wood 2002) thus we might expect the shallow ground waters of playas of the Yarra Yarra catchment to show spatial variability roughly related to the SE-NW rainfall gradient. Low groundwater salinities seen in samples 12–14 possibly represent the diffusive flux (recharge) of low salinity surface waters into the shallow groundwater, presumably with the equivalent upward flux of salts.

Based on the ionic ratios given in Figure 7, it is possible to predict the pathway of shallow groundwater evolution and relate this to the physical hydrology of the playas (Fig. 8). We propose that the shallow ground waters have evolved along the pathway described in Figure 8, *i.e.* pathway 1B, modified from Jankowski and Jacobson (1989). Here, recharge waters have evolved from a low salinity composition, in our case a likely combination of rainwater and regional groundwater, into Na-(Mg)-Cl(SO4) type brines with depleted Ca and HCO_3. Chemical analysis of local rain waters and regional ground waters was not undertaken in this study but would be necessary to confirm conclusively the source and composition of input waters. Nonetheless, the IB pathway requires that the initial waters have a ratio of Ca : HCO_3 of > 0.5 and SO_4: Ca of > 1 which is common to percolated rainwater containing dilute sea-salts (Yechieli & Wood 2002).

Free convective flow (Fan *et al.* 1997; Yechieli & Wood 2002) is likely to contribute to brine evolution in these playas. The playas satisfy the necessary conditions for free convection to occur. According to Fan *et al.*, (1997) these include a shallow water table and resultant 'wet' playa surface and abundant recharge through regional groundwater flow.

Variations seen in the relative proportions of ions in the surface water could be attributed to capturing different phases in the geochemical pathway during evaporative concentration. We identified from ionic ratios that the playas monitored probably followed the 1B geochemical pathway of Jankowski and Jacobson (1989) where, at the first chemical divide (the initial precipitation of calcite), the calcium to alkalinity ratio is < 2 resulting in waters dominated by Na and Cl with appreciable Mg, Ca and SO_4 as seen in samples 1, 2 and 9 (Table 5). At the next chemical divide, gypsum precipitates and if the SO_4 concentration then remains greater than Ca concentration, we derive a Na and Cl dominated brine with appreciable SO_4 and Mg. Therefore, the ground waters chemically appear to be the concentrated end product of evaporated surface waters with reduced Ca possibly due to cation exchange (clay adsorption) during infiltration (Herczeg & Lyons 1991). Similar processes have been documented in other lakes in Australia including Lake Eyre and Lake Tyrell (Jankowski & Jacobson 1989).

Despite the relatively consistent water chemistry observed, discrete variations in ionic composition may prove to be significant to playa biology. For example, the species composition of diatom communities is known to be sensitive to anion concentrations, the effects of which may be concentrated by nutrient availability (Servant-Vildary & Roux 1990; Saros & Fritz 2000a, b). Therefore in addition, catchment inputs should be quantified. This could be particularly important in the Yarra Yarra catchment which is dominated by agricultural landuses, including the widespread application of super-phosphate fertilisers and gypsum soil improvers (Boggs *et al.* in press).

Conclusions

The hydrology of six small playas in the Yarra Yarra drainage system of Western Australia was monitored over two wet seasons. The six playas represent a hydrological continuum of ephemeral basins from mostly wet to mostly dry. The variability seen in hydroperiod and filling frequency was largely dependent on rainfall variability, sub-catchment size and slope and local drainage connectivity.

Ground waters were generally less than 1 m below the playa surface and essentially flat under each playa reflecting the low topographic gradient. While likely to be net discharge playas, there were spatial and temporal variations in hydraulic head indicating that local, shallow groundwater movement is complicated by the presence of surface water and the playas may switch to a recharge mode for short intervals. More widespread investigations of groundwater movement facilitated by a longer monitoring period and more comprehensive piezometer networks as well as measurements of diurnal variations in the watertable are needed to determine the sub-surface flow inputs which would help complete the understanding of hydrochemistry of the playas.

Hydrochemically, the playas were not unlike other playas in Australia. They display a wide range of salinity, neutral to alkaline pH and ionic composition similar to seawater. We postulate that the geochemical evolution of waters in the playas follows the 1B pathway of Jankowski and Jacobson where low salinity recharge waters with seawater salts progress to Na-Cl dominated brines through evaporative concentration. The similarity of groundwater and surface water TDS suggest there is interchange occurring between the two waters.

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